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Getting Detonation Rates from Front Curvature

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Abstract: Many detonation front curvatures are reviewed. Most are of the Shock Dynamics type, which are described as a combination of quadratic and 8th power-of-the-radius curves. The integrated fraction of the 8th power curve is taken as a measure of curvature, which we are able to relate to the logarithm of the detonation rate. This provides a means of estimating the rates of some unknown explosives from the curvature. Using the edge lag divided by the radius is an even better way. A second group of curvatures are almost or purely quadratic. This is probably not associated with density gradients but may be caused by low sound speeds. A final group of “sombros” show curvy fronts for ideal explosives, which appear to be caused by density gradients.

Keywords: detonation front curvature, edge lag, shock dynamics, detonation rate

PACS:

Is it possible to estimate detonation rates from the curvature of a cylindrical front? To get the curvature we shall use normalized coordinates, where L is the lag at radius R and L_0 and R_0 are the edge lag and radius. We then fit the curves to [1]

$$\frac{L}{L_0} = A \left(\frac{R}{R_0} \right)^2 + B \left(\frac{R}{R_0} \right)^8. \quad (1)$$

We integrate each term across the radius from 0 to 1 and derive the area fraction belonging to the 8th-power term, k , which is

$$K = \frac{B/9}{A/3 + B/9}, \quad (2)$$

so that K gives a useful way to define the curvature, given that much of the data is not good enough for more elegant fits.

Figure 1 shows the particle velocity along the radius, and it is clearly continuous from the axis. Both powers of Eq. 1 are mixed in. If we search for a starting radius for the 8th power term, we find that such a fit starts $\frac{3}{4}$ of the way out for all samples.

We have also modeled cylinders and ratersticks using JWL++, a simple descendent of Ignition & Growth, which runs in a CALE-like Lagrange code [2]. All runs were steady state with sufficient square zoning, based on the rule of thumb

$$Z_0 \approx 1 + 0.86v, \quad (3)$$

where Z_0 is the minimum zoning in zones/cm and v is the detonation rate in μs^{-1} . This degree of zoning does detonation velocities correctly but may not be enough to handle the high-frequency 8th power term.

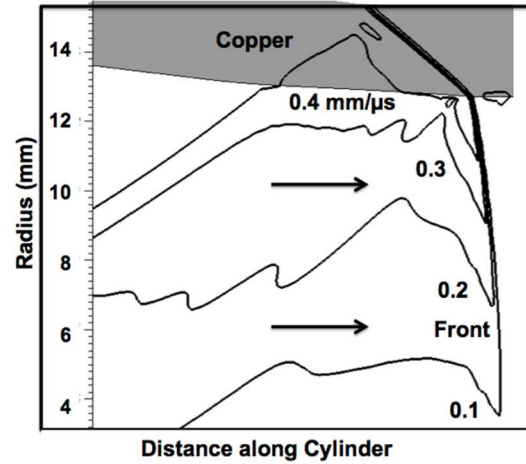


FIGURE 1. Code plot of the confined LX-17 particle velocity along the radius showing how it increases continuously as we move to the edge.

In Shock Dynamics, the curvature defines the detonation velocity. The steady state detonation velocity, U_s , at the radius R_0 may also be related to the detonation rate, v , by the Eyring equation

$$\frac{U_s}{U_s^\infty} = 1 - \frac{U_s^\infty}{v R_0}, \quad (4)$$

where U_s and U_s^∞ are the detonation velocities at radius R_0 and infinite radius. This may be derived from the definition of the rate, which is

$$v = - \frac{(U_s^\infty)^2}{dU_s / d(1/R_0)}. \quad (5)$$

This relates the rate to the inverse of the size effect curve slope. The steady state rate may vary with radius.

SHOCK DYNAMICS CURVES

The first category we have analyzed contains Shock Dynamics explosives, which are mostly unconfined and with uniform textures. The term unconfined includes glass or cardboard tubes. This group includes ANFO, PBX 9502, and nitromethane, which have been fit with Bessel functions by LANL [3-5]. Because these explosives relate curvature to detonation velocity, they should also relate to detonation rate.

In Figure 2, we plot K for these Shock Dynamics explosives along with NM/silica/guar and other ANFO's [6-8], as a function of the detonation rate and find there is a definite trend. The parameter K is constant for all ANFO's, then it rises with increasing rate, starting at about $20 \mu s^{-1}$. All samples were unconfined, except for one PBX 9501. There are 35 good samples with another 15 more scattered examples.

These results may be used to estimate the detonation rate of an unknown explosive if it falls on the slanted line. The LLM-105 explosive, RX-55-AB, has a K value which puts its rate at about that of ultrafine TATB at $110 \mu s^{-1}$. However, the plot goes as the logarithm of the rate, so that the estimate is rough. Unfortunately, we have no PETN data, which would extend the rate up to $1000 \mu s^{-1}$.

JWL++ is low in predicting K from $100 \mu s^{-1}$ and up, which is where sufficient zoning of the cylinder becomes difficult to achieve. From Figure 3, we can also see that a combination of the edge lag and the radius,

L_0/R_0 , with less effort and no curvature analysis, does just as well in estimating the rate. The edge lag is a function of the radius and dividing by the first power is a rough way of trying to create a constant. This method extends down to ANFO, which the curvature method did not.

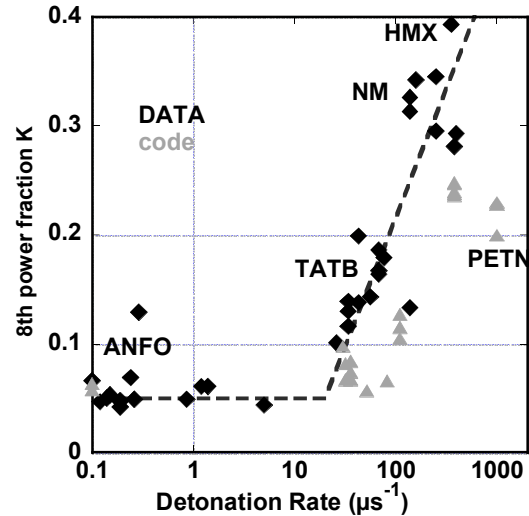


FIGURE 2. Plot of the best-behaved Shock Dynamics explosives with parameter K versus detonation rate.

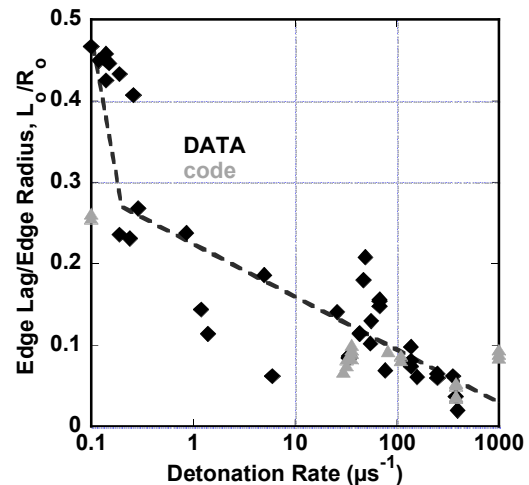


FIGURE 3. The ratio of the edge lag divided by the radius gives a similar result with the detonation rate.

An issue to consider is the effect of radius. In Figure 4, we see that K for unconfined PBX 9502 rises somewhat with

decreasing radius, just as does the rate. For NM/silica/guar, K drops quickly, just as does the rate. Pure nitromethane drops rapidly but its rate is nearly constant, so that its behavior is a mystery.

In general, the higher the detonation rate, the greater is the component of the 8th power, K. For low-rate ANFO, however, k never goes to zero but levels off at about 0.04. JWLL++ simulates the curvature but under-calculates K, except for ANFO, where we can easily over-zone the problem.

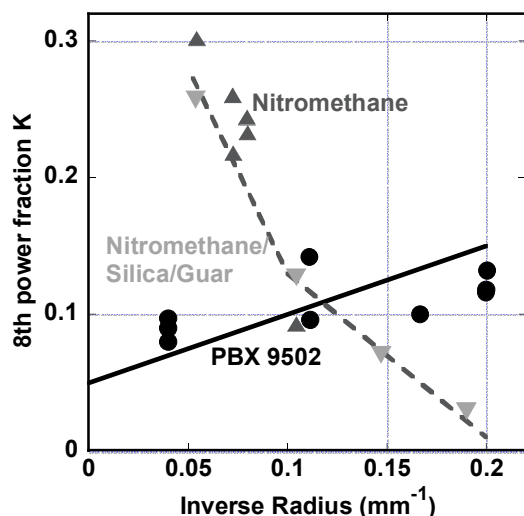


FIGURE 4. Radius dependence of three differently behaved explosives.

The detonation front overall is determined by morphology. For example, a calculated 1.833 g/cc LX-14 curvature gives $K = 0.536$. But suppose the outer 10 to 12.7 mm is at 1.834 g/cc and the inner 0 to 10 mm is at 1.8325 g/cc, a small difference that could occur in pressing. Then K becomes 0.591 and the value of the result as applied to getting the rate is questionable.

SOMBREROS

The second and most spectacular class are the sombreros [9], shown for LX-14 in Figure 5. These are all ideal explosives usually with small edge lags. All were metal-confined and ram-pressed, or in the case of Semtex 1A, stuffed in. Other examples are dense PETN and LX-19 (CL-20).

The reason for these results is almost certainly density differences. Pressing

causes the explosive at the edge to densify over that in the center, so that the detonation velocity will be lower on the axis. This, combined with the radial symmetry, produces the droop at some in-between radius.

This effect only occurs for a high rate explosive like HMX ($380 \mu\text{s}^{-1}$). In a slower explosive like TATB ($45 \mu\text{s}^{-1}$), the entire front locks together with no dip ever appearing.

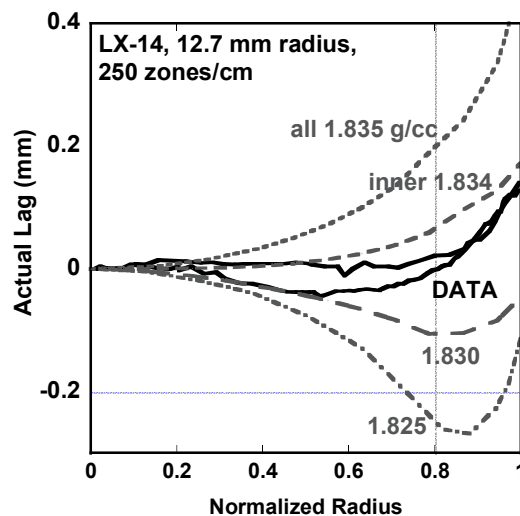


FIGURE 5. Modeling the sombrero in confined LX-14 by lowering the inner 0 to 10 mm to lower densities. A combination of 1.832 g/cc inside and 1.835 g/cc outside appears to fit. The high rate does not allow the dip to straighten out.

QUADRATIC CURVES

A third group contains non-Shock Dynamics explosives. We have nine good examples, where Eq. 1 shows no 8th power component. Another 5 samples are close and another dozen show less 8th power than expected.

The best examples include: confined low density ammonium perchlorate (12 μm), LX-20 (HMX paste), PBXN-111 (aluminized RDX and more) and unconfined RDX 70/urethane [9-12]. All are metal-confined except for the RDX/urethane. Four curves are shown in Figure 6.

The only way to model this behavior is to make a slice of explosive near the edge have a lower density than in the center. For RDX/urethane, we had to lower the density

from 1.45 g/cc to 1.35 g/cc on the edge. Even so, the result looked discontinuous.

Again we look to morphology. It seems possible that 30% of binder might damp out the high frequency edge effect. Enough inert material or space might break up efficient mass transfer. This can never be seen in our code, because all explosives are considered continuous and the speed of sound is locked to the JWL.

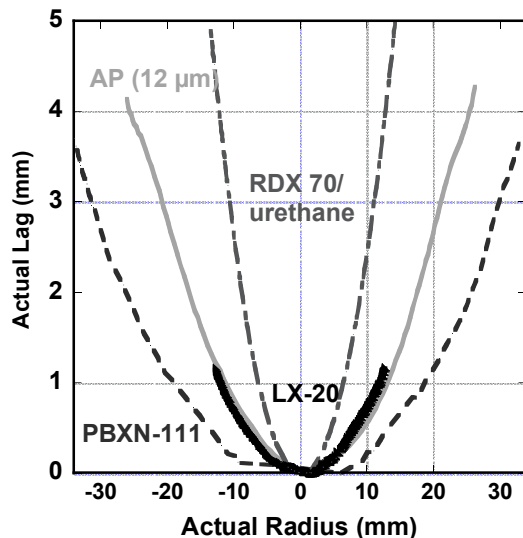


FIGURE 6. Four different explosives with quadratic curves.

In summary, detonation rates can be roughly obtained from detonation front curvature if the density is uniform, the explosives crystals small and the binder low. Any deviation from this produces results more dependent on the explosive morphology.

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